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Liquefaction mapping with a geographic information system Monterey County, CA

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LIQUEFACTION MAPPING

WITH A GEOGRAPHIC INFORMATION SYSTEM

MONTEREY COUNTY, CA

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ABSTRACT

LIQUEFACTION MAPPING WITH A GEOGRAPHIC INFORMATION SYSTEM MONTEREY COUNTY, CA.

by John Matthew Gurley

This thesis addresses the use of a Geographic Information System (GIS) for mapping potential liquefaction areas in Central Monterey County, California. Currently no large scale maps showing areas susceptible to liquefaction exist for this part of the county. This GIS study uses the existing digital database map of the Monterey County soils survey to combine soil units into Quaternary geologic units by geomorphic surface type then differentiates the geologic units by age to create maps of liquefaction suceptibility. The Quaternary geologic units are tabulated and the typical depth to ground water for each unit is estimated from existing ground-water maps. The units which can become water saturated are identified by liquefaction susceptibility criteria from very low to very high. These maps can be used to identify areas where liquefaction may occur. A GIS provides an effective use of existing data to produce these digital database maps.

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(in pocket rear leaf)

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CHAPTER 1

INTRODUCTION

Monterey County, California, is an area with a high potential for large earthquakes, because the San Andreas Fault and other faults are within the county's boundaries (see fig. 1). The San Andreas Fault has a history of large earthquakes above M5.0 on the Richter Scale. One of the results of these large earthquakes is ground failure due to liquefaction of water-saturated, unconsolidated sedimentary deposits. These ground failures can cause damage to engineered structures and injury to people. Liquefaction has occurred during these major earthquakes in the North County around Monterey Bay and to a lesser extent in the Salinas River Valley, south of Salinas (Youd and Hoose 1978 and Tinsley et al. 1998). Knowledge of liquefaction susceptibility, as a seismically related hazard, is important for land use planning in Monterey County.

The digital mapping of zones of liquefaction susceptibility is an important way to display this information. Currently only small scale paper maps show the seismic hazard zones of the Salinas River Valley south of Salinas and these maps show estimates of ground shaking in terms of the modified Mercalli intensity (MMI) scale.

Liquefaction susceptible zones are not shown on these paper maps. The North County area surrounding Monterey Bay was mapped on paper by Dupre and Tinsley (1980) and digitally mapped by Pike et al. (1994) to show liquefaction susceptible zones.

The concern of government agencies with the effects of earthquakes has led to requirements for mapping seismic hazards on a statewide basis (Phillips 1998; Lerable 2000; Peterson 2001). California requires the mapping of all seismic hazards (California Code of Regulations 1990). The Seismic Hazards Mapping Program (California Department of Conservation 1998) has developed guidelines for identifying and mapping liquefaction susceptible zones. Seismic Hazard Zones are areas meeting one or more of the following criteria:

1. Areas known to have experienced liquefaction during historic earthquakes.
2. Areas of uncompacted fills that may become saturated.
3. Areas where sufficient existing geotechnical data and analyses indicate that soils are potentially liquefiable.
4. Areas where geotechnical data are insufficient to provide large scale liquefaction susceptibility maps per the Seismic Hazards Mapping Program.

The Salinas River Valley south of Salinas meets criterion one, as the area has experienced liquefaction during the 1906 earthquake. Criterion two is met in small, scattered areas, but not considered in this study, but no location data have been found. Insufficient geotechnical data are available to meet the third criterion. The area of the Salinas River Valley encompasses over 375 square miles. The geotechnical testing or data, such as Standard Penetration Tests (SPT) or Cone Penetration Tests (CPT) and grain size distribution, required to map the liquefaction susceptibility on a regional scale, has been done at only a few sites (less than 20). Geotechnical testing is usually done on a site-specific basis and identifies seismic conditions for that particular site.

Monterey County's Department of Planning and Building Inspection building permit files were reviewed for the period from 1975 to 1994 (data beyond 1994 had not been cataloged). Only two permit files with accompanying geotechnical data were found. Files from the City of Gonzales provided data for five additional sites within their city limits. Site reports for the areas around Highway 101 bridges are available from the California Department of Transportation, but these data cover only a small percentage of the area.

A review of other geotechnical studies (Falls 1988; Rosenberg 1998) indicates that a large number of data points are required to adequately map even a small area. In the case of the Falls's study of San Jose, California, data from over 1500 sites were collected and in the case of the Rosenberg study of Hollister, California, data from over 300 sites were collected. The cost of doing additional geotechnical testing at the rate of $100+/hour for a large region such as Monterey County would be prohibitive (Grice 1999).

The fourth criterion is also met, as adequate geotechnical testing has not been done at enough sites to provide large-scale maps of liquefaction susceptibility in the area south of Salinas. Therefore, liquefaction susceptible mapping can only be done using geologic criteria rather than geotechnical criteria to determine areas containing water saturated, unconsolidated deposits (river channels, flood plains, basins, alluvial fans, and terraces) of the late Pleistocene to recent Holocene age (see table 1).

According to King (1994), there are problems in using geotechnical criteria for mapping seismic hazards on a regional scale. When insufficient geotechnical data are available, mapping can be completed using a Geographic Information System (GIS) and existing digital databases and other published data. A GIS can input large amounts of spatial and tabular data on a regional scale and present the results in a manner useable for liquefaction susceptibility hazard planning. In this study a GIS was used to differentiate and analyze existing digital databases to create geologic and liquefaction susceptibility maps. The final maps show areas with liquefaction susceptibility based on the geology, age of the deposits, and potential depth to ground water. These maps provide planning information for the Monterey County government agencies and others to define liquefaction susceptibility zones. These techniques are transferable to other geographic areas for liquefaction susceptibility studies.

Goals

The primary goal of this study was to demonstrate the use of existing data resources and a GIS to make maps of seismic hazards, in this case, liquefaction susceptibility. A secondary goal was to create maps of the Quaternary geology and liquefaction susceptible zones. Another secondary goal was to tabulate the typical depth to ground water of each Quaternary geologic unit.

Specific steps to reach these goals were:

1. Review the Quaternary geologic data and soil data in the study area and determine if these data are sufficient to create a digital database map.
2. Determine how to combine the soil units by their geomorphic surface and how to differentiate the geologic units by age.
3. Create a digital database map showing the Quaternary geology of the area.
4. Differentiate the geologic map units with graduated degrees of liquefaction susceptibility (low to very high) based on the age of each unit and ground slope
5. Review recorded depth to ground-water data.
6. Use the depth to ground-water data from step 5 to correlate for each geologic unit its liquefaction susceptibility.

Given that insufficient geotechnical data are available, the use of other existing data are required to achieve the project goals. Prior projects mapping liquefaction susceptibility have used existing geologic and hydraulic data. The use of a GIS is a more recent addition to the methodology. This evolution will be discussed in the following chapter.

CHAPTER 2

OVERVIEW

Previous Studies

The models for liquefaction susceptibility mapping have used either quantitative or qualitative procedures. The quantitative procedure is based on geotechnical data such as SPTs or CPTs and grain size distribution. The qualitative procedure is based on Quaternary geology, geomorphic data and depth to ground-water data (less than 50 feet). This study used the qualitative analytical procedure because of insufficient geotechnical data.

The mapping of liquefaction susceptibility began in the 1970's using the qualitative procedure (Youd 1991). The early paper maps were compiled from existing geologic maps and the depth to the water table was compiled from existing data or was measured. An extensive database of these earlier studies was created compiling the effects of major earthquakes throughout the world (see tables 1 and 2). The criteria listed in table 1 were developed from the many areas of the world that experienced major earthquakes and where liquefaction had occurred (Youd and Perkins 1978). The type of geomorphic surface and the age of the Quaternary deposit (see table 1) combined with the depth to ground water (see table 2) determined the liquefaction susceptibility of these deposits. Additionally Lajoie and Halley (1975), Iwasaki et al. (1982), Dupre (1990) and Ishihara and Yasuda (1991) have used these criteria to identify and map zones of liquefaction susceptibility. Recent studies (Sowers et al. 1998 and Knudsen et al. 2000) also used this model. A recent example of providing liquefaction susceptibility on a regional basis is the Association of Bay Area Governments' World Wide Web (WWW) site (ABAG 2001). The San Francisco Bay Region's liquefaction susceptibility map is displayed on the WWW site using an interactive GIS.

Table 1. Estimated susceptibility of unconsolidated sedimentary deposits due to liquefaction during strong seismic shaking. After Dupre and Tinsley (1980).

Type of deposit	Distribution of unconsolidated sediments in deposits	Likelihood that unconsolidated sediments, when saturated, would be susceptible to liquefaction, by age of deposit.				
		<1000 years	Late Holocene	Early Holocene	Late Pleis-tocene	Early Pleis-tocene
Stream Channel	Locally variable	Very high	High	Moderate	Low	Very low
Younger flood plain	Locally variable	Very high-high	Moderate	Low	Very low	Very low
Older flood plain	Locally variable	Moderate	Low	Very low	Very low	Very low
Basin	Locally variable	High-moderate	Low	Very low	Very low	Very low
Alluvial Fan	Widespread	Moderate -low	Low	Very low	Very low	Very low
Terrace	Widespread	Low	Low	Very low	Very low	Very low
Dune lands	Widespread	Moderate -low	Low	Very low	Very low	Very low

Table 2. Probable liquefaction susceptibility of unconsolidated, granular, non-gravelly layers as criteria used to compile a liquefaction map. From Dupre (1990) and Tinsley and Fumal (1985).

Age	Depth to Ground Water			
	0-10 feet	10-30 feet	30-50 feet	50 feet +
Present to late Holocene	Very high to high	Moderate	Low	Low
Early Holocene	High	Moderate	Low	Very low
Late Pleistocene	Low	Low	Very low	Very low
Early Pleistocene	Very low	Very low	Very low	Very low

Location and Description of the Salinas River Valley

The Salinas River basin drains an area of approximately 4,000 square miles in Monterey County. The Salinas River is about 170 miles long with the lower 93 miles on the Salinas Valley floor from near Wanpost to Monterey Bay (see fig. 3). The Salinas Valley is the largest of the California coastal intermountain valleys. The Santa Lucia Range on the west separates the basin from the Pacific slope. The Gabilan Range and the Diablo Range separate the basin from the San Joaquin Valley and the San Benito Valley on the east.

The river has its headwaters in the area above Paso Robles in San Luis Obispo County and three major tributaries from the west and two smaller tributaries from the east side join the river. The valley floor extends from the county's southern boundary north to the Pacific Ocean near Castroville and encompasses about 375 square miles (see fig. 3).

The normal total precipitation on the valley ranges from 9 to 13 inches per year and typically occurs between November and March. The precipitation on the west-side mountains is about twice (2/3 of total) that on the east-side mountains (1/3 of total). About 70% of the total runoff (California Department of Public Works 1946) comes from the watersheds on the west side of the valley between Spreckles and Wunpost (see fig. 3). The Monterey County Water Resources Agency has divided the Salinas Valley Basin into five ground water areas based on sources of ground water replenishment. The areas are (1) Pressure, (2) East Side, (3) Forebay, (4) Arroyo Seco Cone and (5) Upper Valley (see fig. 3).

Thick, impermeable layers of blue clay confine the water in the "Pressure" area in aquifers at 180 and 400 feet below the ground surface. The only confined aquifers are in the "Pressure area". These aquifers are recharged from the "Forebay" area. Small areas near Quail Creek and at the southeastern end of the "Pressure" area, near Gonzales, have an unconfined aquifer. Other small areas have perched water tables closer to the ground surface above the 180-foot aquifer. These perched areas can only be located by examining the individual well logs.

The drillers' well logs have a place to show depth to first water. A review of over 100 well logs indicates that these data were not reported in a large majority of logs. Determining the location of the perched water tables would be difficult without these data.

The other areas of the valley have unconfined aquifers that are recharged by percolation from the Salinas River or ground water from the other areas and by the streams that are headed in the mountains. In years when the precipitation exceeds the average (greater than 13 inches) some direct percolation does occur into the water table.

The base map for this study is of the Quaternary geology of the Salinas River Valley. To create this base map, knowledge of the character of the soils, their depositional environment and geomorphology is necessary. The following discussion is a summary of these features.

The soils in the river valley are divided into four major classes:

1. Those in the stream channel in the bottomlands adjacent to the river
2. Those on the river flood plains
3. Those on elevated terraces and fans
4. Those on stream bottoms along creeks

The soils in the bottomlands have clay or silty clay textures. The soils on the flood plains next to the river have fine sandy loam and silty clay loam textures. The soils on terraces and fans above the bottomlands have sandy and coarse sandy loam textures. The soils on the stream bottoms have coarse sandy loam textures.

According to Tinsley (1975), the sedimentary deposits in the Salinas River Valley consist of alluvial fans and terraces, fluvial terraces, and flood plains. The area has a history complicated by active tectonics and the combined impacts of sea level and climate changes in the Tertiary and Quaternary. The alluvial fan deposits from the Santa Lucia and the Gabilan mountain ranges incise the older Salinas River fluvial deposits on the west and east sides of the valley. The alluvial fan deposits from the area north of Soledad contain only igneous and metamorphic rocks and no sedimentary rocks. The parent materials of the fluvial deposits are of sedimentary origin and are from the headwaters of the Salinas River and its tributaries. This contrast between the parent materials provides a means to distinguish the sediments in the valley fill.

According to Harradine (1963), the soils in the Salinas River Valley are characterized as non-calcic Brown soils. These soils occur in North America only in the inland valleys in northern California. Their occurrence is based, a semi-arid Mediterranean climate with two seasons. Hot dry summers have minimum precipitation and July average temperatures of 62-82 degrees F and cool wet winters have 9-13 inches precipitation and January average temperature of 45-52 degrees F. Non-calcic Brown soils develop at a uniform and slow rate, because of these semi-arid climate conditions. Five stages of soil profile development have been identified in non-calcic Brown soils; undeveloped, minimal, medial, maximal, and maximal with hardpan. The age of the geomorphic surfaces and the geologic map units is based on these stages of profile development.

The integration of the different soil units of the valley into specific Quaternary geologic units is dependent on knowing the type of geomorphic surface and the texture and the parent material of the individual soil units. The use of this information will become evident in the methods discussed in the next chapter.

CHAPTER 3

THE CASE STUDY

Area of the Study

The study area, as shown in figure 2, is along the Salinas River Valley from south of Salinas to Greenfield (North Latitude 37 degrees 30 minutes to 36 degrees 15 minutes) and east of the Santa Lucia Range, and west of the Gabilan Range (West Longitude 121 degrees 37.5 minutes to 121 degrees 7.5 minutes). This area is shown on the Chualar, Gonzales, Palo Escrito Peak, Soledad, Pariaso Springs, and Greenfield 7.5-minute quadrangle maps (U.S. Geological Survey 1984). This area was chosen because it is and will likely continue to experience the most rapid population growth and development in the cities south of Salinas. To grant building permits, the local planning departments need seismic hazard (liquefaction) data to help ensure the safety of buildings and other engineered structures.

The particular areas of study for liquefaction susceptibility are those deposits of Holocene and late Pleistocene age on or adjacent to the river valley bottomlands. Empirical data (see table 1) show that these deposits are the most susceptible to liquefaction (Youd and Perkins 1978). The areas have flat or gentle sloping geomorphic features such as river terraces, flood plains, alluvial fans, and terraces. The geomorphic surfaces in the surrounding mountains of the Salinas River Valley are Middle Pleistocene age and older and have a very low susceptibility to liquefaction and were not analyzed in this study These areas are situated more than 50 feet above the water table and because of their age are very consolidated and indurated (Youd 1991 and Iwasaki et al. 1982).

Methods

Liquefaction susceptibility mapping. Mapping was done on the basis of three factors:

1. The presence of unconsolidated sedimentary deposits
2. The presence of a ground-water table that has a history of rising to within at least 30 feet of the ground surface
3. A historical record of liquefaction during previous earthquakes

The procedures used to assess these factors are:

1. To map the Quaternary geology on the basis of geomorphic surface and age
2. To map the liquefaction susceptible deposits based on the Quaternary geology
3. To determine the typical depth to the ground water in each geologic unit
4. To correlate the typical depth to ground water with each geologic unit's liquefaction susceptibility

GIS methods. A GIS was used to create the base map and the derivatives of the base map. The planimetric base map was created showing the county's boundaries, streets and major towns. Digital maps of polygons representing each of the different soil units were imported into the GIS to create a soil unit thematic map. The soil unit polygons were combined for each geomorphic surface type and became a polygon of each geologic map unit. Each geologic map unit was integrated into one map depicting the Quaternary geology of the study area. The final map was created by differentiating the Quaternary geology map into age units based on the degree of soil profile development. This thematic map was differentiated again to show only the areas with slopes between 0-2%. Digital Orthophoto Quads (DOQs) of the area were imported into the GIS as image polygons and were used to help differentiate the geomorphic features and the associated soil units.

Mapping the Quaternary geology and geomorphic surface age. Geologic maps can be created from existing geological paper maps or created from existing digital database maps. Dibblee (1974) mapped the Monterey County region but did not differentiate the Quaternary geology. Tinsley (1975) did the original mapping of the Quaternary geology of the northern Salinas Valley. Two ways were available to create a digital database map of the Quaternary geology for this paper. The first way was to use the existing soil series' digital database map of Monterey County (California Coastal Commission 1997). The other way, depended on making a digital database map from the paper maps in Tinsley's dissertation (1975); these maps could not be digitized because of their large size.

Creating the Quaternary geology map involved visual interpretation of the existing soil series digital map, reviewing individual soil descriptions (Cook 1978) and comparing U.S. Geological Survey (USGS) topographic maps and DOQ's of the study area. The soil series descriptions provided soil profile development, parent material, geomorphic surface, texture, and slope data. A review of Tinsley's dissertation (1975) provided a methodology for combining soil series map units into geologic units and the use of soil profile development data to determine the relative age of geologic units.

The soil units were combined into geomorphic surface categories in the present environment as shown in table 3 and became the Quaternary geologic units as shown in table 5. Using the relative soil profile development (age) of each geologic unit, the geologic units were differentiated into groups by the degree of profile development. The degree of profile development (age) created a new map showing the potential for liquefaction susceptibility, as the age of the geologic units corresponds to potential for liquefaction. Several authors (Lajoie and Helley 1975; Birkeland 1990, 1984, 1974; Birkeland et al. 1991; Dupre and Tinsley 1980) have used these methods.

A soil-geomorphic surface study was made to approximate the relative ages of the surface soils. Soil-geomorphic studies track the sequence of soil development with time. The Salinas River Valley is an example of a post incisive sequence, called a stepped river-terrace sequence where each soil in the sequence began to form when a new terrace was formed. A cross section of the Valley shows a series of terraces at different elevations above the river and thus the sequence of each geomorphic surface's relative age (see figs. 10a, 10b, and 10c).

Table 3. Geomorphic surface categories

Stream channel	Dune land
Alluvial fan and terrace	Banks and escarpments
Basin	Flood plains

The estimated age of each geomorphic surface was determined by the degree of soil profile development. The soil profile is the zone from the ground surface to 3 to 5 feet below the ground surface and is divided into horizons, primarily A, B, and C. Soil scientists have identified the characteristics of a profile based on depth to each horizon, color, texture and clay and carbonate content in each horizon and other features. These characteristics are used to determine the degree of profile development. The existing soil profile data (Cook 1978) show each soil unit's profile development. The transfer into and transformation of clay minerals in the B-horizon and the oxidation of iron in the B-horizon are the primary indication of the age of the deposit. The geologic units were combined into five age groups by degree of soil profile development using the principles of soil stratigraphy (Morrison 1967; Ruhe 1956). The five degrees of profile development are undeveloped, minimum, medial, maximal, and maximal with hardpan as defined by Harradine (1963) for non-calcic Brown soils (see table 4).

Three of the Quaternary geologic map units were field checked for a qualitative comparison of the degree of profile development. The three units were younger alluvial fan, Chualar terrace, and Gloria terrace. The younger alluvial fan was loose, unconsolidated medium to fine sand (undeveloped). The Chualar terrace was well consolidated and indurated, a rock hammer made very small indentations (maximal development). The Gloria terrace was well consolidated and indurated, a rock hammer made no indentations (maximal development with hardpan).

Mapping liquefaction susceptibility. The geologic map was used to produce a map showing the zones of liquefaction susceptible soils as described by Youd and Perkins (1978). The zones were mapped using the criterion of low, moderate, high, and very high susceptibility, according to the age (profile development) of the deposit (see table 1).

A further differentiation was made of the liquefaction susceptible soils into those areas with slopes of 0-2%. The slope data were obtained from the *Soil Survey of Monterey County* (Cook 1978) and are shown in table 7.

Table 4. Soil profile development and age modified from Harradine (1963). Soil horizon nomenclature in accord with Soil Survey Staff (1975).

Age of Deposit	Profile Development	Horizons
Youngest	Undeveloped	A no B horizon
	Minimal	A12, B2, B3 horizons
	Medial	A3, B2t, B21 and B31 horizons
	Maximal	A3, B1, B2t, B31, B32 horizons
Oldest	Maximal with hardpan	A3, B1, B2t, Cm horizons

Ground water. The relative susceptibility of geologic deposits of each type is determined by depth to ground water and the deposit's potential for becoming saturated. The typical depth to ground water was determined using existing ground-water data in the study area. The liquefaction susceptibility varies from very low to very high depending on the age of the deposit and depth to ground water (see table 2). Monterey County maps showing lines of equal depths to water in the fall of 1944 (California Department of Public Works 1946) provided a means to estimate the typical depth to ground water for each Quaternary map unit. The younger geologic units are closer to the Salinas River on the valley floor and the depth to ground water is less than 30 feet. The older geologic units are higher in elevation and further from the River and the depth to ground water is greater than 30 feet and some of the older Quaternary units are greater than 50 feet.

Geotechnical and geologic data comparison. A comparison was made between liquefaction susceptibility determined by geotechnical reports of seven different locations and the results of this study for the same locations. This was done as a check on the overall accuracy of this study. The geotechnical reports made determinations of liquefaction susceptibility based on Standard Penetration Tests (SPT) and depth to ground water. These reports made a determination of liquefaction using the categories of low, medium, and high susceptibility. The geotechnical determinations were compared with this report's determinations using the Quaternary geologic unit's susceptibility for the same map location. The geotechnical and geologic liquefaction susceptibility data for each location was tabulated (see results).

Data

The primary digital data source was the WATER CD (California Coastal Commission 1997). The WATER data sets use the Universal Transverse Mercator projection (UTM) and the North American Datum (NAD) 1983, distance in meters. The necessary data to perform a susceptibility assessment using geologic criteria were as follows:

Soils and Quaternary Geology. The *Soil Series of Monterey County* (Cook 1978) data were digitally mapped by the U.S. Soil Conservation Service and are contained on the WATER CD (California Coastal Commission 1997). These data were the basis for creating a digital database map describing the Quaternary geology. The soils were individually named based on their unique characteristics. They were shown on the digital database map and each soil had its individual description in the database file attached to each map unit. (see appendix A, table A-1). Additionally, Cook (1978) contained each soil's profile development, parent material, texture, engineering properties, typical geomorphic surface, and general geographic location.

Liquefaction can cause different kinds of ground failure depending on the ground slope. The types of ground failure and associated slope are lateral spread (0-3% slope), flow failure (greater than 3%), ground oscillation (0-0.3%) and loss of bearing strength (0.0%) (University of Washington 2000). The soil survey data provided for each individual soil are divided into subsets by the slope of the deposit surface, 0%, 0-2%, 0-5%, 2-5%, and 2-9% slope. These slope values were those used in Cook (1978). Each soil map unit's slope value is shown in table 7. The most critical slopes considered were 0% and 0-2%. Slopes above 5% were not considered in this liquefaction study because the depth to ground water is in general greater than 50 feet and has very low liquefaction susceptibility.

The map unit names and descriptions of the Central Salinas River Valley Quaternary geology are listed in table 5 and a complete description of each unit is in appendix B.

Table 5. Geologic map units, from Tinsley (1975) as modified by this author to use consistent unit descriptions and subscripts from Dupre and Tinsley (1980) and Pike et al. (1994). A full description of each map unit is included in Appendix B.

Geologic unit	Abbreviated description
Qsc	Modern stream channels.
Qyf	Younger floodplain (Metz).
Qof	Older floodplain (Salinas)
Qb	Basin deposits.
Qf	Younger alluvial fan surfaces and associated deposits.
Qan	Antioch terrace.
Qch	Chualar alluvial fan surfaces and associated deposits.
Qp	Placentia alluvial fan surfaces and associated deposits.
Qgl	Gloria alluvial fan surfaces and associated deposits.
Qod	Dune sand.
in	Unknown deposit
al	Bluffs, banks and escarpments
ba	Badlands
d	Dumps

Depth to ground-water data. The Monterey County Water Resources Agency (WRA) provided access to the water well logs and ground-water level data. The historical ground-water level data were collected on a periodic schedule (semi annual) from certain monitoring wells from 1944 to the present. Additional historical data from 1930 to 1959 are contained in the *Salinas Basin Investigation* (California Department of Public Works 1946, 1949, 1950, 1952) and *Ground-Water Conditions* (California Department of Water Resources 1964). The contour maps showing depth to water from the ground surface in 1944 are included in the *Salinas Basin Investigation* (see figs. 4 and 5). The WRA uses the 1944 ground-water level as the baseline for annual changes in ground-water level. The WRA provided graphs showing the annual changes from the 1944 baseline in ground-water level for each area. As described above in Location and Description, the "Pressure" area ground waters are from artesian aquifers and thus water well data are not an indication of unconfined ground-water level. In these areas, data on the unconfined ground-water surface level are limited. Some perched water tables exist in the "Pressure" area. An attempt to locate these areas was made and over 100 well logs were reviewed. The indication of the depth to first water was not reported in a high percentage of the logs. It is not clear if the practice was to leave this out or was just the preference of individual drillers.

Geotechnical data. Monterey County Department of Building Inspection and Planning and the City of Gonzales provided building permit files containing geotechnical data. These files were reviewed and a limited number (seven) contained reports regarding SPTs, soil information, and liquefaction potential in the study area. These files represented about 5% of the total.

Historical data. Historical data from the 1906 earthquake of liquefaction sites in Monterey County were from Youd and Hoose (1978) and Lawson and others (1908). Tinsley et al. (1998) summarized the historical data from the 1989 Loma Prieta earthquake. Evidence from historical earthquakes is a consideration in determining liquefaction susceptibility. Ground failure will have a probability of reoccurring at the same location about 80% of the time if the magnitude and the distance from the subsequent earthquake epicenter are equivalent (Knudsen et al. 2000).

Supplemental data. The 7.5 minute paper topographic maps (United States Geological Survey 1984) were used to verify geomorphic features by evaluating elevation contour lines and comparing them with the soils at that location. The changes in topography often are an indication of a change in soils. Use was made of many digital database maps to show country boundaries, streets and towns (California Coastal Commission 1997).

CHAPTER 4

RESULTS

Quaternary Geology of the Central Salinas Valley

A Quaternary geology map was created. The maps of the north and south parts of the study area are shown in figures 6 and 7. The scale and location system used for the maps is 1:75,000 and the California State Plane Coordinate System, zone 4, North American Datum 1927. Distances are in feet. The digital map databases are accurate to a scale of 1:24,000 and are available in digital PDF files. Each Quaternary geologic unit (**Q**) is identified by a different color. The Salinas River bottomlands, and the terraces and fans on each side of the valley closer to the mountain fronts, are the main focus of the study because most of the unconsolidated sedimentary deposits occur there. The Salinas River watercourse is identified as **Qsc**. The youngest deposits nearest to the river are the younger floodplain (**Qyf**), basin deposits (**Qb**), and older floodplain (**Qof**). The younger alluvial fan deposits (**Qf**) are further from the river and are on the downslope of areas that originate in the streams that incise the gullies between the older alluvial fans and terraces (**Qch, Qan, Qp,** and **Qgl**).

To create these maps, several intermediate steps were necessary. Each soil's description in Cook (1978) assigns its geomorphic surface, its parent material and its texture. Twenty-two soil series were identified in the study area and the individual soil series names are shown in table 6.

DOQs were used to visually differentiate the geomorphic surfaces and verify each soil's location. All soils with the same name are correlated for all locations into data sets in the GIS and each data set is assigned a geologic map unit name (Q) and unique identifier, (sc). The geologic units with their soil sets, parent material, and type of geomorphic surface are shown in table 7. This table was made from integrating the individual soil units into Quaternary geologic map units.

Table 6. Soil Series of Monterey County in the study area, extracted from WATER (CA Coastal Commission 1997) and Cook (1978). The names are the Soil Survey map units.

Antioch	Danville	Metz	Salinas
Arroyo Seco	Elder	Mocho	Sorrento
Chualar	Gloria	Pacheco	Tujunga
Clear Lake	Gorgonio	Pico	Badlands
Cropley	Hanford	Placentia	Dunes
Psamments and fluvents		Xerorthents	

The soil profiles for each soil set shown in table 6 are contained in the *Soil Survey Monterey County, California* (Cook 1978). See appendix A, (table A1) for the specific profiles of each soil series. The geologic map units from table 7 with similar degrees of profile development, and thus age, were grouped together as shown in table 9. The differentiation by age is shown in table 4.

Table 7. Combining of soil units into geologic map units. Identification name is by Quaternary (Q) geologic map unit (see table 5). Full details of each individual soil unit's texture are shown in Appendix A (table A1).

Geologic map unit	Description of geomorphic surface	Parent material and slope, %	Soil series names
Qyf	Younger floodplain	Sedimentary rock, 0%	Metz and Pico
Qof	Older floodplain	Sandstone and schist, 0-2%	Salinas, Sorrento, Pacheco
Qb	Basin deposits	Sedimentary rock, 0-2%	Clear Lake, Cropley, Mocho
Qf	Younger alluvial fans and fluvial terraces	Granite and sedimentary rock, 0-2%	Arroyo Seco, Elder, Hanford, Tujunga
Qch	Chualar alluvial fan and terrace	Granite and schist, 0-2%	Chualar and Danville
Qan	Antioch alluvial fan and terrace	Sedimentary rock, 0-2%	Antioch
Qp	Placentia old alluvial fan and terrace	Granite and schist, 0-2%	Placentia
Qgl	Gloria fan and terrace	Granite, 0-2%	Gloria
Other units			Soil map unit
Qsc	Modern stream channel	Undifferentiated, 0%	Psamments, fluvents
al	Steep uplands, bluffs, banks	Undifferentiated	Xerorthents
Qod	Dune lands	Granite	Dune lands
in	Unknown	Undifferentiated	Indeterminate
ba	Eroded cliffs, gullies	Undifferentiated	Badland

A comparison was made between the Quaternary geology maps produced by Tinsley (1975) and the maps generated by this project. Tinsley defined the Salinas terrace or high flood plain as combining the more sandy soils, the finer textured sandy soils and poorly drained, fine textured clay rich soils into one map unit (Tinsley 1975, 57). This paper separated the moderately fine textured loamy soils and the fine textured clayey soils (see table 8) into two separate map units, **Qof** (older flood plain) and **Qb** (basin). This difference can be seen in comparing the textures in Appendix A, table A-1. Other geologic map unit differences were minimal between the two studies.

Table 8. Groupings of soil texture classes (Soil Survey Staff, 1975).

General Terms	Texture Classes
Sandy soils: Coarse textured	Sands (coarse, fine sand, very fine sand) Loamy sands (loamy sand, loamy fine sand and loamy very fine sand)
Loamy soils: Moderately coarse textured	Coarse sandy loam, sandy loam, silt loam and silt
Medium textured	Very fine sandy loam, loam, silt loam, silt
Medium textured	Very fine sandy loam, loam, silt loam and silt
Moderately fine textures	Clay loam, sandy clay loam, silty clay loam
Clayey soils: fine textured	Sandy clay, silty clay and clay

Table 9. Liquefaction Susceptibility, Quaternary map units differentiated by soil profile development, age and resulting liquefaction susceptibility. Modified from Dupre and Tinsley (1980).

Geomorphic surface and geologic map unit at 0-2% slope	Soil profile development	Age, years	Liquefaction susceptibility
Qsc- Stream Channel	Undeveloped and minimal	1-500	Very high/high
Qyf- Younger flood plain		1-500	Very high/high
Qof- Older flood plain		500-5000	Moderate
Qb-Basin deposits		1-10,000	High/moderate
Qf-Younger alluvial fan		1-5000	Moderate/low
Qch- Chualar alluvial fan and terrace	Medial	30,000-80,000	Low
Qan- Antioch and **Qp**- Placentia alluvial fan and terrace	Maximal	<50,000-160,000	Low
Qgl- Gloria alluvial fan and terrace	Maximal with hardpan	<250,000- >1,600,000	Low

Liquefaction Susceptible Deposits

The determination of liquefaction susceptibility of sedimentary deposits is based on the type of geomorphic surface, age of the deposit, slope of the ground, and the degree of the deposit's water saturation. The potential for liquefaction susceptibility are compiled using the criteria from table 1. The qualitative degree of susceptibility (very low, low, moderate, high, and very high) of each geologic unit is shown in table 9. The geologic units which have a very high, high, moderate, and low susceptibility are compiled from table 9 and these units with a slope of 0-2% are shown in table 7. Figures 8 and 9 show very high, high, moderate, and low liquefaction susceptibility for areas with 0-2% slope. The legend shows each geologic map unit and its color with its degree of susceptibility.

The potential for liquefaction increases as the depth to the ground-water table decreases (see table 2). The depth to ground water is a variable dependent on ground-water recharge from percolation, precipitation, and recharge from pumping. The areas that may be saturated because of the ground-water depth are shown by the contour maps (see figs. 4 and 5) from 1944 data and are used as a base line to monitor annual average changes of level in each of the County's water supply areas (see fig. 3). Before 1944, California Department of Water Resources (1964) monitored the water level changes in each area. The highest recorded high ground-water level, as shown from these two sources, occurred in the winter of 1940-41. The rainfall in that year was 250% of normal. Approximating the ground-water change from the base line year of 1944 for the contour maps, the decrease in depth to the water level for 1940-41 is "East Side" area (–) 6 feet, "Forebay" area (–) 7 feet, and "Arroyo Seco Cone" area (–) 12 feet.

A determination of susceptibility was made for each type of geologic unit based on an estimated typical depth to ground water based on the existing contour maps. The contour maps have a minimum contour depth to ground water of 20 feet (see figs. 4 and 5). For this determination the contour lines on the map, 20, 30, 30, 40 feet, etc. are used as the depth to ground water. The recorded high in 1944 is ignored (average change in ground-water level is minus 8.3 feet for 1941). The contour maps would be accurate enough to make an estimate of each geologic unit's typical depth to ground water. Figures 6 and 7 (Quaternary geology) and figures 4 and 5 (depth to ground water) were used to make this estimate by comparing the contour lines and each geologic unit's typical geographic location. Each geologic unit's susceptibility and typical depth to ground water are correlated in table 9.

The historical data from the 1906 earthquake on the San Andreas Fault (Youd and Hoose 1978 and Lawson 1908) show extensive ground fissures and sand boils in the flood plains adjacent to the Salinas River as far south as Camphora. There was extensive structural damage and lateral spreading at Spreckles and lateral spreading at the Gonzales Road Bridge where it crosses the Salinas River.

There was no evidence of ground failure in the study area during the 1989 Loma Prieta earthquake (Tinsley et al. 1998).

Table 10. Geologic units indicating liquefaction susceptibility based on depth to ground water. Historical indication of liquefaction in prior earthquakes (Youd and Hoose 1978).

Geologic unit	Historic Liquefaction	Typical Ground-water depth, ft.	Depth to ground water, ft. and Liquefaction susceptibility			
			0-20	20-30	30-50	>50
Qsc	Yes	< 20	**VH**	VH	H	M
Qyf	Yes	<30	VH	**H**	M	L
Qof	Yes	<30	H	**M**	L	VL
Qb	Uncertain	<30	H	**M**	L	VL
Qf	No	>50	M	L	VL	**VL**
Qan	No	>50	L	VL	VL	**VL**
Qch	No	>30	M	L	**L**	VL
Qp	No	>40	L	L	**VL**	VL
Qgl	No	>50	L	VL	VL	**VL**
Qod	Uncertain	<30	VH	**H**	M	L

The historical occurrence of liquefaction in each geologic unit is shown in table 10 and the probability of reoccurrence based on the typical depth to ground water for each geologic unit. Liquefaction susceptibility is shown in terms of very high (VH), high (H), moderate (M), low (L), and very low (VL). Bold symbols indicate the most likely occurrence of liquefaction.

The geotechnical criteria data were compared with the liquefaction susceptibility maps created using geologic criteria data (see table 11). Because the geotechnical data are site specific, they are probably the more accurate determination of liquefaction susceptibility. The geotechnical data sites are shown on figure 8. Sites 4 and 5 show a significant difference. The geologic map data show areas with high and moderate to high susceptibility, and the geotechnical site-specific data show moderate to low and low susceptibility. This may be because the sites are on the boundary between two geologic units and the site specific data are more accurate.

Table 11. A comparison between geotechnical data from building permit geotechnical reports and geological based liquefaction susceptibility maps.

Site number	Geotechnical data	Geologic unit and map criteria	Depth to ground water greater than 30 feet
1	Moderate to low	**Qp** - Low	Yes
2	Low	**Qp** - Low	Yes
3	Moderate to high	**Qb** - Moderate to high	Yes
4	Moderate to low	**Qyf** - High	Yes
5	Low	**Qb** – Moderate to high	Yes
6	Moderate to low	**Qgl** - Low	Yes
7	Moderate to low	**Qgl** - Low	Yes

CHAPTER 5

SUMMARY AND CONCLUSIONS

Summary

The primary goal was to demonstrate that digital maps of potential liquefaction hazards could be created using existing data and a GIS (see figs. 8 and 9). A secondary goal was to create a digital map of the Quaternary geology of the Central Salinas Valley (see figs. 6 and 7). The Quaternary geology map was used as a basis to determine the liquefaction susceptibility of the deposits that were susceptible to liquefaction. Another secondary goal was to tabulate typical depth to ground water data to show which deposits could become saturated and could liquefy during an earthquake. The maps should be useful for land use planning by many organizations including the Monterey County Department of Planning and Building Inspection and other Monterey County agencies. This all has been accomplished with the use of a GIS, available digital database maps, and data compiled from published resources. The geologic criteria maps are for determining potential liquefaction hazards on a regional planning basis and not for individual sites.

The study area contains unconsolidated deposits that could liquefy when saturated and cause ground failure during a large (>M 5.0) earthquake. The area of concern for this liquefaction susceptibility study is in the Central Salinas Valley and generally adjacent to the Salinas River and parts of the Arroyo Seco

River. The geologic units where the potential for water-saturated deposits may exist are shown in table 9.

Conclusions

As demonstrated in this study and other recent studies (Knudsen et al. 2000), a GIS can be used to provide regional digital database maps for use in seismic hazard planning. The availability of digital databases, especially soil series database maps, made this study feasible. The part of the Salinas River Valley south of this study could constitute a follow-on project. There are some different soils in this area and a new digital database would have to be created. Soil series digital maps are available now for all or parts of 35 counties in California (Natural Resources Conservation Service 2001). A continuing task would be to create digital liquefaction hazard maps for other counties in California and make these liquefaction hazard maps available to the general public by using the WWW (World Wide Web) as a resource database. This can be done once the original databases are created (ABAG 2001). The Central Coast Data Committee of Monterey, Santa Cruz, and San Benito Counties has undertaken the task of making regional digital database maps available to the public, using GIS, on their WWW site.

APPENDIX A

Table A1. Monterey County Soil Survey representative soil profile descriptions. From Cook (1978). Soil texture abbreviations and modifiers are from the sand, silt and clay textural triangle and soil texture descriptions (Soil Survey Staff 1975).

TEXTURAL ABBREVIATIONS

C Clay	SCL Sandy Clay Loam
CL Clay Loam	SL Sandy Loam
L Loam	Si Silt
LS Loamy Sand	SiC Silty Clay
S Sand	SiCL Silty Clay Loam
SC Sandy Clay	Silt Loam

MODIFIER ABBREVIATIONS

vf	very fine
f	fine
co	coarse
vco	very coarse
g	gravelly

Table A1

Soil Series	Horizon	Depth,inches	Soil Texture
Antioch, Ae	Ap	0-4	SL
	A12	4-15	SL
	A2	15-21	SL
	B21t	21-27	SL
	B22t	27-32	C
	B23t	32-40	CL
	B31tca	40-52	CL
	B32tca	52-67	SCL
Arroyo Seco, As	Ap	0-5	SLg
	A12	5-18	SLg
	A13	18-29	SLg
	C1	29-42	SLg
	IIC2	42-60	Slgvco
Chualar, Cb	Ap	0-7	L
	A12	7-21	L
	B1t	21-30	SL
	B21t	30-44	SCL
	B22t	44-55	SLgf
	B3	55-59	SLfgco
	C	59-80	Sfgco
Clear Lake, Cf and Cg	A11	0-18	C
	A12	18-24	C
	C1	24-33	SiCL
	C2	33-54	SiL

Table A1 - Continued

Soil Series	Horizon	Depth, inches	Soil texture
	IIC3	54-62	LSvf
Cropley, Cn	A11	0-4	SiC
	A12	4-25	SiC
	A13	25-36	SiC
	ACea	36-46	SiC
	C1ca	46-55	SiC
	C2	55-69	SiC
	C3	69-76	SiCL
Danville, Da	Ap1	0-5	SCL
	Ap2	5-18	SCL
	B2t	18-38	C
	B3t	38-53	SCLg
	C1	53-67	SCLg
	C2	67-78	CL
Elder, Ea and Eb	Ap	0-9	SL
	A12	9-22	SL
	A13	22-37	SL
	IIC1	37-52	SLfg
	IIC2	52-73	LScog
Gloria, Gh	Ap	0-8	SL
	A12	8-15	SL
	A2	15-16	SL
	B2t	16-23	C
	C1sim	23-41	hardpan

Table A1 - Continued

Soil Series	Horizon	Depth, inches	Soil texture
Gorgonio, Gk	Ap	0-7	SL
	A12	7-22	SLco
	AC	22-35	LS
	C1	35-48	LSg
	C2	48-63	LSgf
Hanford, Hb	A11	0-7	SLg
	A12	7-33	Lg
	IIC1	33-43	LgSco
	IIC2	43-70	LgSco
Metz, Me, Mf and Mg	Ap	0-12	SLf
	C1	12-29	Sf
	C2	29-38	S
	IIC3	38-52	SLvf
	IIIC4	52-118	Sf
Mocho, Mn and Mo	Ap1	0-7	SiCL
	Ap2	7-12	SiCL
	C1ca	12-21	SiCL
	C2	21-24	SiL
	C3	24-45	SiL
	C4	45-68	SiL
Pacheco, Pa and Pb	Ap	0-8	CL
	A12	8-16	CL

Table A1 - Continued

Soil Series	Horizon	Depth, inches	Soil texture
	A13	16-22	CL
	IIC1g	22-35	SiCLf
	IIC2g	35-47	CL
	IIIC3g	47-65	CL
Pico, Pf	Ap	0-8	SLf
	A12	8-18	SLf
	C1ca	18-40	SLf
	IIC2ca	40-45	SiCL
	IIIC3	45-55	SL
	IVC4	55-72	SLvf
Placenta, Pn	Ap1	0-5	SL
	Ap2	5-12	SL
	A2	12-13	SL
	B21t	13-20	C
	B22t	20-29	C
	B23tca	29-36	CL
	B24t	36-42	SCL
	B3t	42-58	SCL
	C	58-68	SLg
Salinas, Sa and Sb	Ap1	0-5	CL
	Ap2	5-13	SiCL
	A13	13-23	SiCL
	A14	23-33	SiCL
	C1	33-40	SLvf
	C2	40-49	SLvf

Table A1 - Continued

Soil Series	Horizon	Depth, inches	Soil texture
	C3	49-75	SLf
Sorrento, Sr	Ap	0-6	CL
	A12	6-15	CL
	A13	15-25	CL
	C1	25-36	L
	C2	36-54	L
	C3	54-78	SL
Tujunga, Tb	A1	0-10	Sf
	C1	10-24	Sf
	C2	24-42	Sf
	C3	42-60	S

APPENDIX B

Description of geologic map units from table 5. Geologic map units and descriptions from Tinsley (1975) and Dupre (1990) as modified for this study.

Qod - Dune land: Consists of loose, well-sorted, fine to medium grained sand. Eolian dunes overlie parts of the Metz and Salinas floodplains near the Arroyo Seco River. 0-100 feet thick.

Qsc - Modern stream channels: Channel deposits of the Salinas River and principal tributaries. Consists of loose, moderately to well sorted coarse to fine grained sand, silt, gravel and cobble.

Qyf - Younger floodplain: Modern, lower floodplain of the Salinas River and principal tributaries. Consists of pebbly, moderately to well-sorted medium to fine-grained gravel, sand and silt. Gravel content increases towards the Arroyo Seco River. Parts of the Metz terrace are flooded seasonally. Capped by undeveloped to minimally developed soils.

Qof - Older floodplain: Modern, higher flood plain of the Salinas River and principal tributaries. Consists of moderately to well-sorted medium to fine-grained silt and sand deposited during high floodwater events. Capped by undeveloped to minimally developed soils.

Qan - Antioch terrace: Oldest flood plain deposits of the Salinas River. Consists of semi-consolidated, moderately well to poorly sorted sand, silt and clay with interbedded gravel. Thickness locally exceeds 100 feet. Terrace surfaces consist of moderately well drained, maximally developed soils; some expansive soils may be present.

Qb - Basin deposits: Deposits in flood basins from standing or slowly moving water episodes of flooding by the Salinas River. Consists of unconsolidated organic rich silt, silty clay and clay.

Qf - Younger alluvial fan surfaces and associated deposits. Consists of unconsolidated, moderately sorted to poorly sorted sand and silt grading into coarse gravel near fan heads and in canyons and narrow, incised reaches within alluvial fans. Capped by undeveloped to minimally developed soils.

Qch - Chualar alluvial fan surfaces and terraces. Consists of weakly consolidated, slightly to moderately weathered, irregularly interbedded moderately to poorly sorted gravel, sand and silt. Gravel content increases near fan heads. Capped by medially developed soils.

Qp - Placentia alluvial fan surfaces and associated and associated deposits. Consists of weakly to semi consolidated, moderately weathered irregularly interbedded to poorly sorted gravel, sand and silt. Gravel content increases near fan heads. Capped by maximally developed soils.

Qgl - Gloria alluvial fan surfaces and associated deposits. Consist of moderately consolidated, moderately to deeply weathered, irregularly interbedded moderately to poorly sorted gravel sand and silt. Gravel contents increases near fan heads. Capped by maximally developed soils with hardpans.

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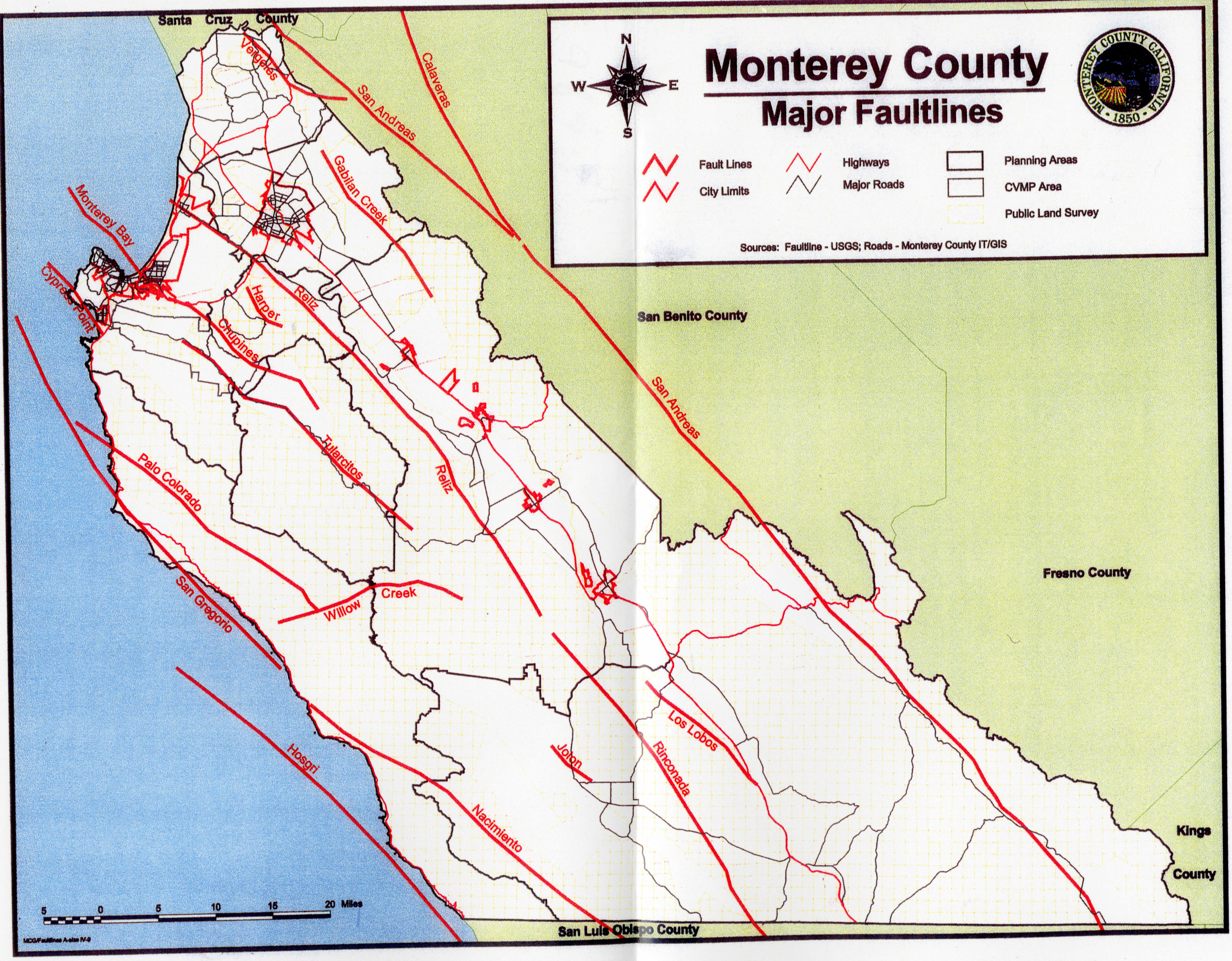

Figure 1. Monterey County major faultlines (Monterey County General Plan Update 2001)

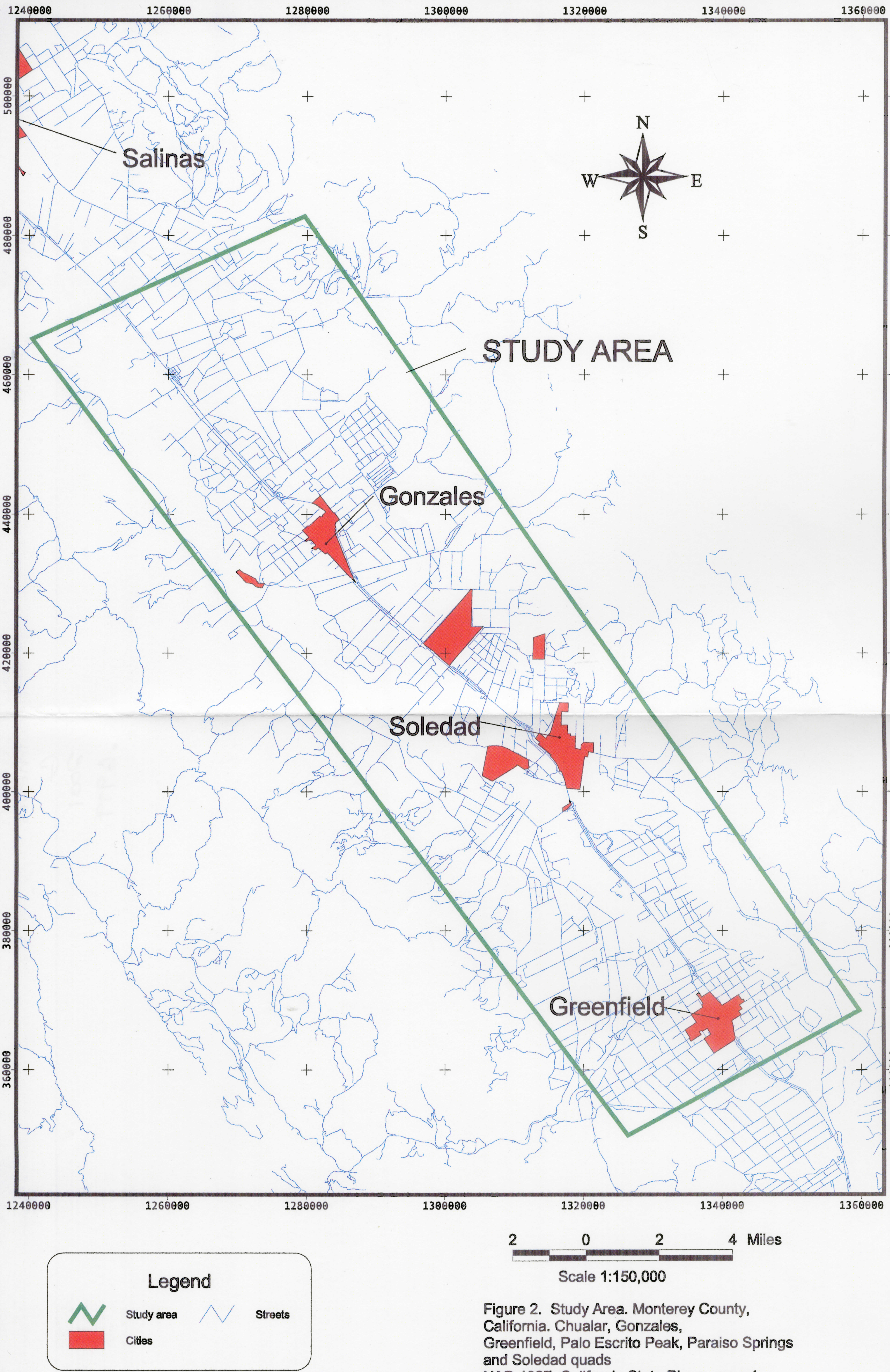

Figure 2. Study Area. Monterey County, California. Chualar, Gonzales, Greenfield, Palo Escrito Peak, Paraiso Springs and Soledad quads
NAD 1927, California State Plane, zone 4

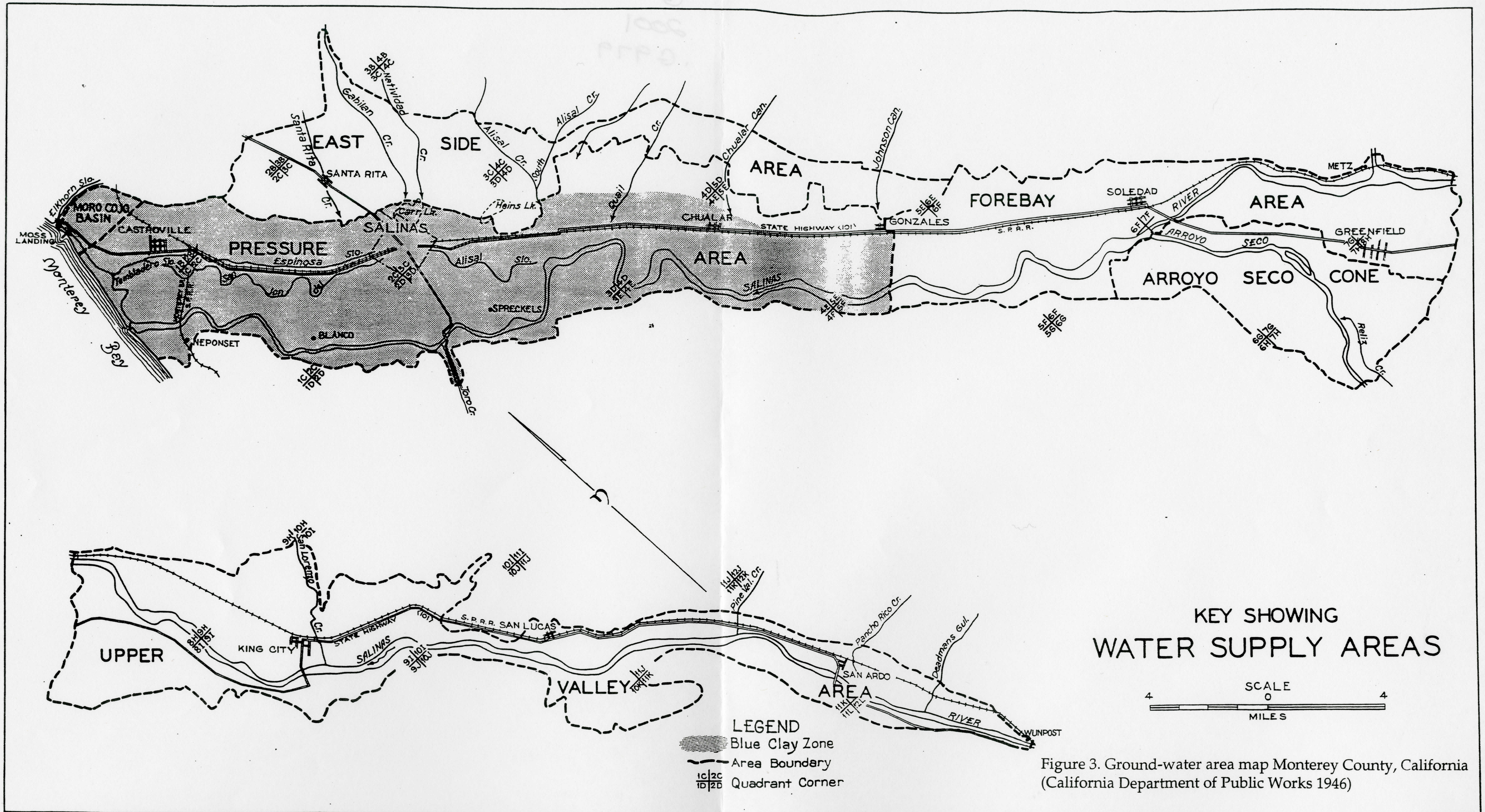

Figure 3. Ground-water area map Monterey County, California (California Department of Public Works 1946)

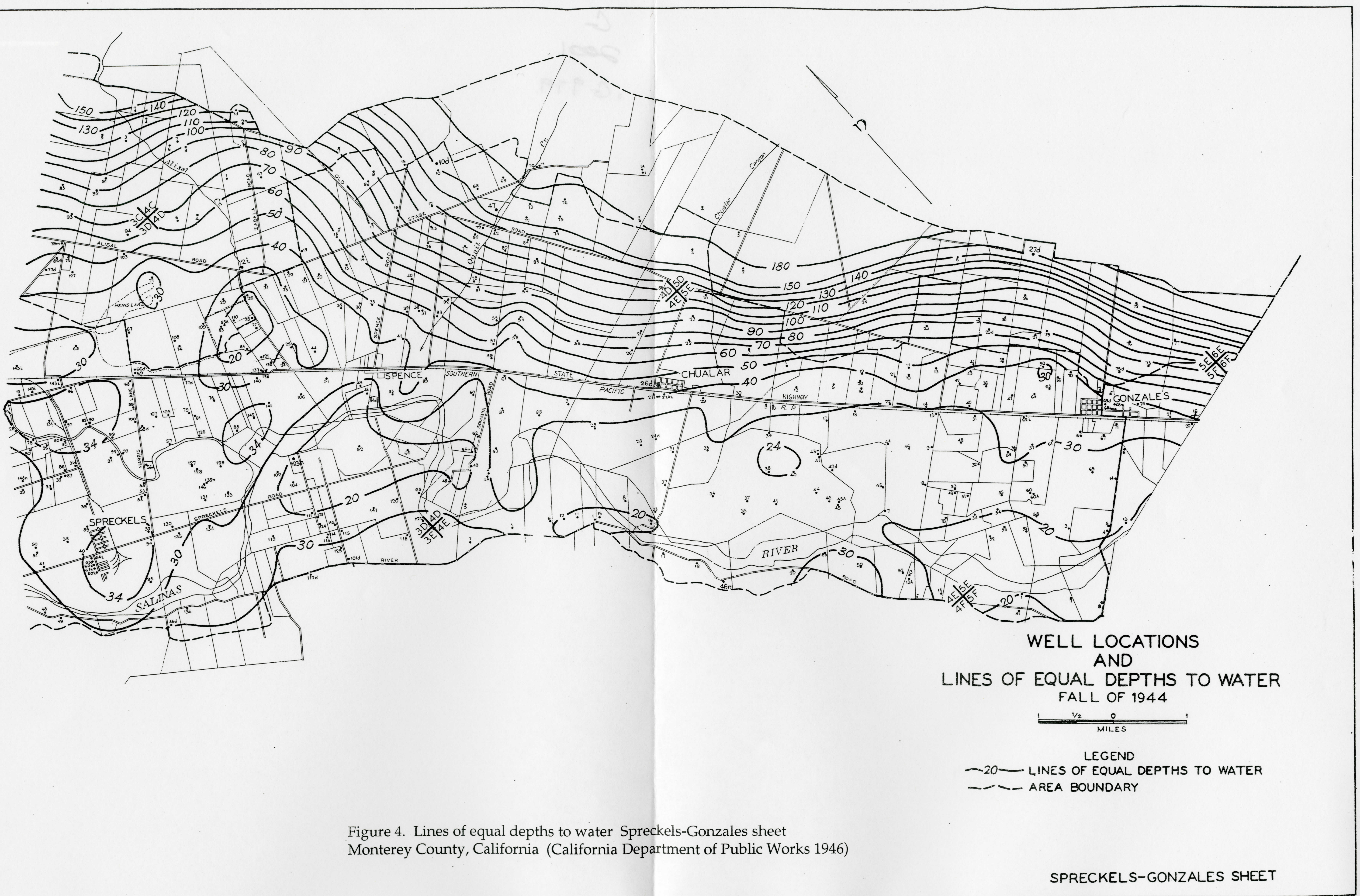

Figure 4. Lines of equal depths to water Spreckels-Gonzales sheet
Monterey County, California (California Department of Public Works 1946)

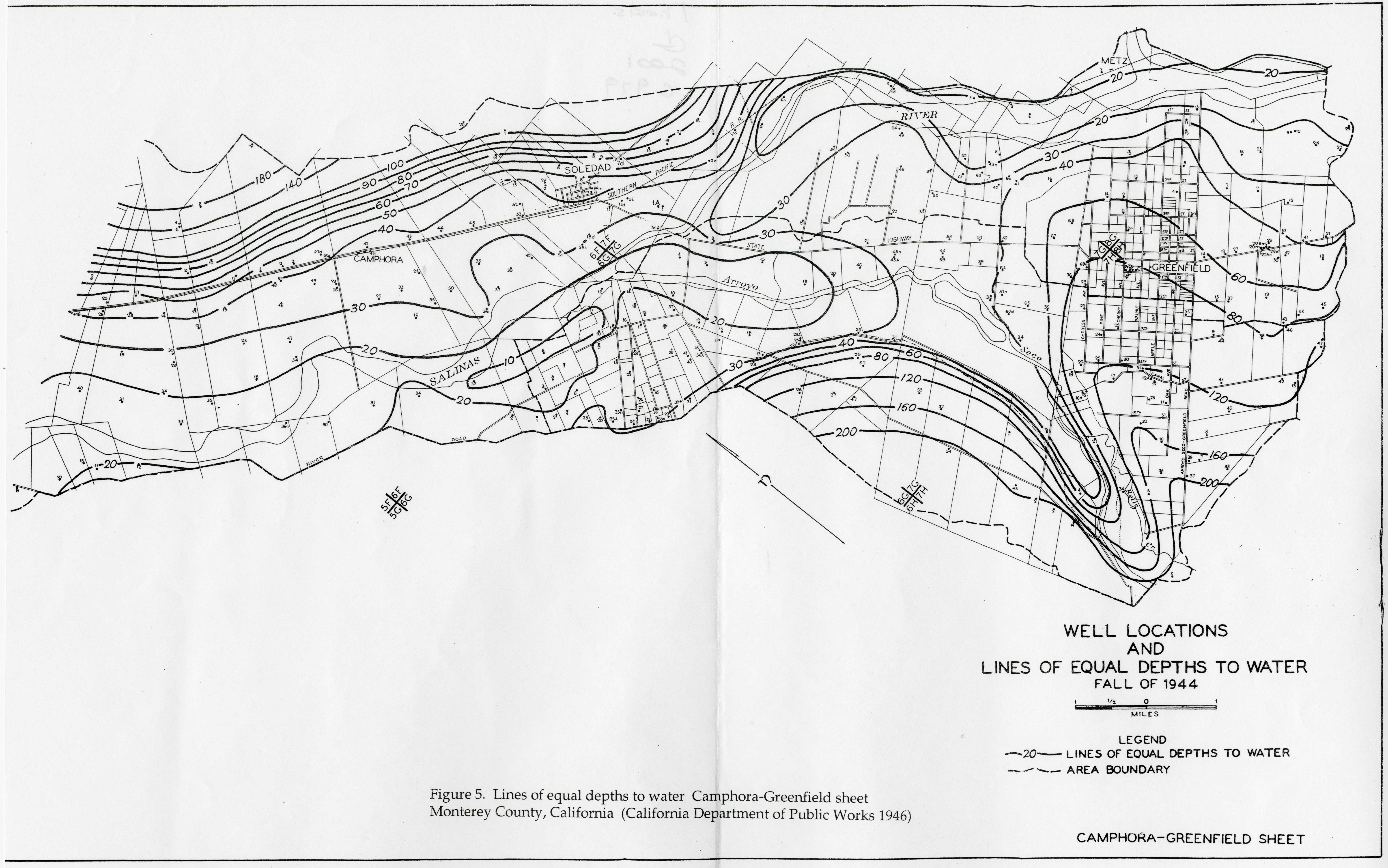

Figure 5. Lines of equal depths to water Camphora-Greenfield sheet
Monterey County, California (California Department of Public Works 1946)

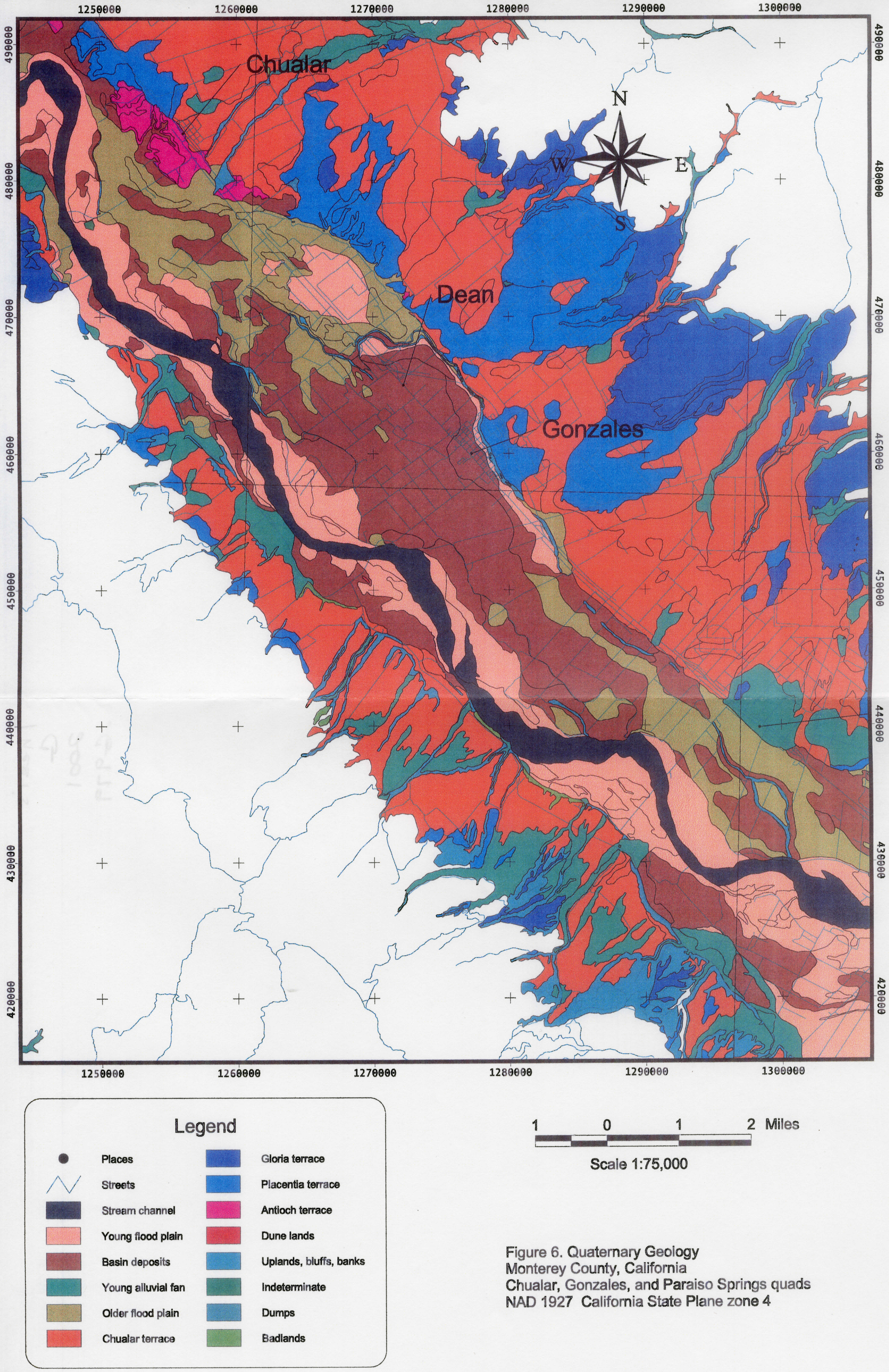

Figure 6. Quaternary Geology
Monterey County, California
Chualar, Gonzales, and Paraiso Springs quads
NAD 1927 California State Plane zone 4

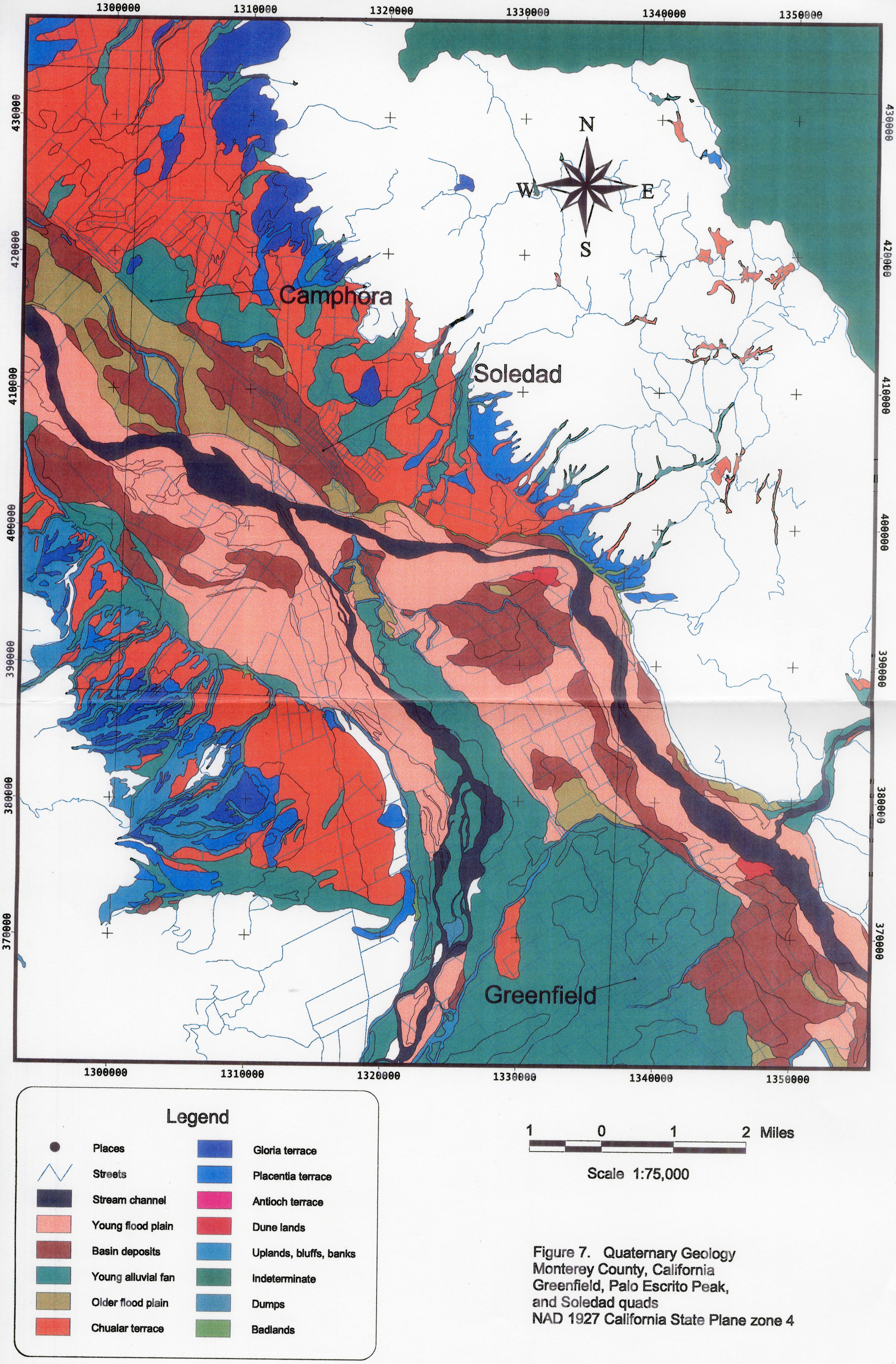

Figure 7. Quaternary Geology
Monterey County, California
Greenfield, Palo Escrito Peak,
and Soledad quads
NAD 1927 California State Plane zone 4

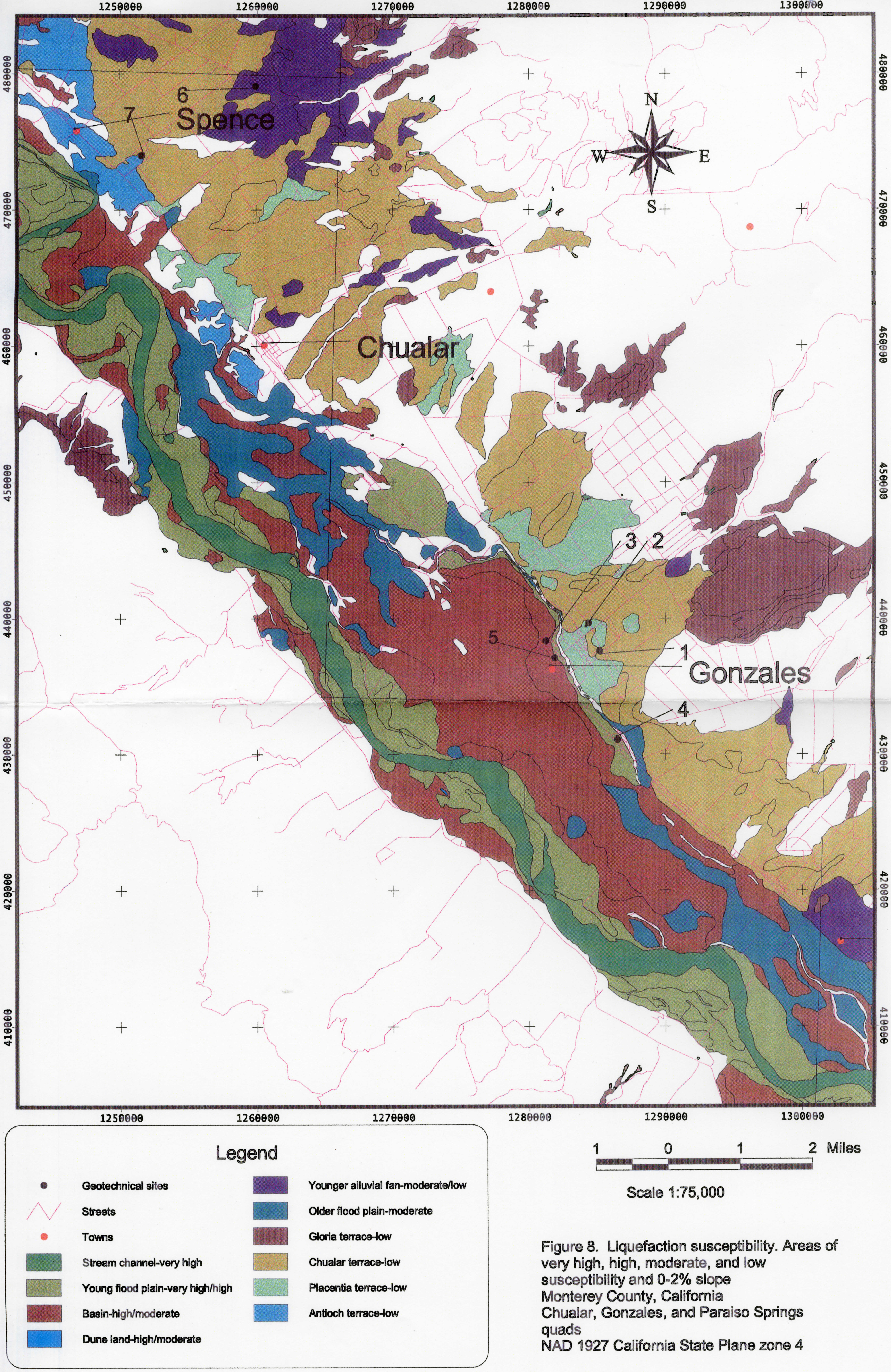

Figure 8. Liquefaction susceptibility. Areas of very high, high, moderate, and low susceptibility and 0-2% slope
Monterey County, California
Chualar, Gonzales, and Paraiso Springs quads
NAD 1927 California State Plane zone 4

Figure 10a. West side Salinas River Valley showing
incised terraces and fans.

Figure 10b. West side Salinas River Valley showing
Chualar terrace and younger alluvial fan.

Figure 10c. Salinas River flood plain.
Salinas River in mid foreground